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Acoustic and Elastic Properties of Modified Oak Wood

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This paper presents studies on acoustic and elastic properties of ammonia modified oak wood compared with parallel testing of unmodified oak control specimens. For evaluation ammonia-modification effects two testing devices were used – portable Timber Grader MTG (Brookhuis Micro-Electronics) and special ultrasonic strength meter, developed at Kaunas University of Technology. Variable physical-elastic-acoustic and size factors of specimens were focused on comparative specification the measurement accuracy and validation applicability of used instruments for testing specific wood properties. Essentially, getting reliable results responding actual wood anisotropy and local structural non-homogeneities was problematic when using tested devices separately. Even more complicated was reliable estimation of viscous-elastic changes and plasticization effects caused by thermo-chemical wood modification. Increased assurance was achieved when using both testers simultaneously.

Keywords: dynamic Young`s modulus, coefficient of damping, ultrasound, wood modification.

INTRODUCTION

Wood as anisotropic and inhomogeneous material has wide spectrum and variation of physical and elastic properties. Wood knots, fissures, spiral grain, early/late wood ratio, etc. make characterization of certain properties extremely difficult [1, 2]. Detection and evaluation of such formations could be equivalently sophisticated as tested wood substance and structure. Non-destructive testing methods (NDT) for investigation of wood specimens and especially large dimension timber become more and more popular [3, 4]. These methods allow enhancing species and grade populations for structural timber though requiring at the same time permanent and adequate control measures. Critical condition for scientific and industrial NDT applications is measuring uncertainties and overall accuracy [5].

Extensive researches on characterization of ultrasound velocity in wood are carried out nowadays. Ultrasound velocity is considered as very sensitive to wood structure variation. Its numeric value depends on wood species, moisture content, grain direction, temperature, density, etc. [6 – 8]. Furthermore ultrasound testing methods are applied for testing of growing trees, cloned or aged wood [9 – 11].

Chemical ammonia modification is used to change wood color and resonant performance. Due to such modification wood physical and mechanical properties change to different extent. Ammonia reduces cellulose microfibrils to elementary fibrils. Consequently a water-soluble substance occurs in cell walls. That causes higher hygroscopicity of ammonia modified wood compared with unmodified. However wood ammonia modification remains many questions on plasticization proportions, colorings, extent of structural changes influencing physical-mechanical properties. Emerging new testing methods focused on wood characterization on micro and nanoscales seems to be revolutionary in understanding breaking by ammonia treatment intra-molecular hydrogen links [12].

As mentioned above, there are many reports on the research about nondestructive testing of wood. However, few investigations have been concerned with wood structural anisotropy and in-homogeneities and their changes after ammonia modification. Insufficient is data on comparative nondestructive testing based on usage of different methods and instrumentation. To complement existing knowledge validation of NDT using portable timber grader MTG (Holland) and special ultrasonic strength meter developed at Kaunas University of Technology was performed [13]. The aim of this work focuses on comparative specification the measurement accuracy and validation of applicability and sensitivity of above-mentioned instruments for testing modification-affected elastic and acoustic wood properties.

MATERIALS AND METHODS

European oak timber was selected for the experiments. Oak wood pieces were cut into samples with 751 mm length, 75 mm width and 24 mm thickness respectively. Then wood was modified with ammonia in special industrial autoclave. The average specimen wood density was 658.3 kg/m^3 and initial average moisture content for unmodified oak wood samples was 9 % while that for the ammonia-modified wood was 12 %.

Series of experiments started with testing wood stress-strength properties using Timber Grader MTG. The measurement principle of the Timber Grader MTG is based on acoustic-wave propagation in the wood. It measures the natural frequency of timber piece. After that the software calculates the stiffness and strength – dynamic modulus of elasticity and related strength class. Coefficient of damping was calculated from graphs generated by special “Timber Grader” software.

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After completion testing with Timber Grader MTG every specimen (modified/unmodified) was examined with special ultrasonic strength meter developed at KTU. The non-destructive ultrasonic Lamb wave's measurement method for determination of hardboard bending strength (modulus of rupture) was applied. The essence of this method is that the velocity propagation of ultrasonic waves depends upon their propagation environment Young's modulus, density and Poisson's ratio [13].

Measurements were performed on four specimen planes denominated Side 1 (S1), Side 2 (S2), Edge 1 (E1) ir Edge 2 (E2). Specimen width was changed by planing repeatedly every 6 mm on edges and for changing thickness successive 3 mm planing on sides was performed. Longitudinal ultrasound scanning was performed gradually on every particular specimen plane at 10 steps (zones). Twofold objectives have been achieved this way: variable specimens' (modified/non-modified) anisotropy due to unfolding new grain configurations and size factor effects to be examined using both testing instruments.

Most of today's acoustic testing methods and calculated elastic constants describe simplified model based on orthotropic wood elastic constants. Such fundamental approaches remain rather theoretical due to experimental complicity and weak adequacy to real wood properties and behavior. Moreover, for applied wood research acoustic scanning along the grain provide sufficient information for estimation timber element structural performance. Such scanning was performed in our study and for that after measuring sound velocity (time-of-flight), generalized modulus of elasticity (MOE) was calculated from simplified equation:

$$MOE = C^2 \rho , \qquad (1)$$

where C is the sound velocity, m/s; ρ is the wood density, kg/m^3.

For evaluation of wood plastic properties, another amplitude-frequency characteristic – coefficient of damping – is used [14]:

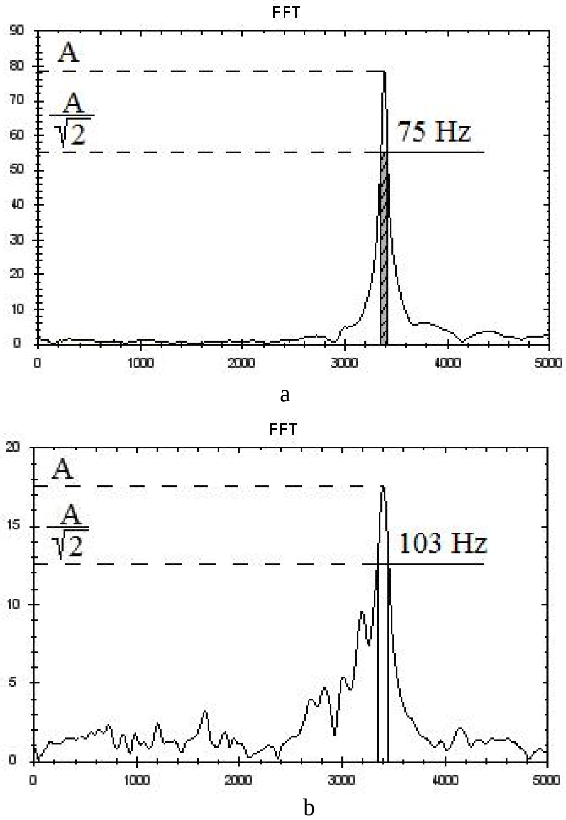
$$\mathrm{tg}\delta \approx \eta = \frac{f_2 - f_1}{f_{res}} , \qquad (2)$$

where tgδ is the tangent of loss angle; η is the coefficient of damping; f_{res} is the resonance frequency; f_1, f_2 is the frequencies with amplitudes by $\sqrt{2}$ smaller than resonant amplitude.

RESULTS

Typical amplitude-frequency characteristics for modified and non-modified oak are presented on the Fig. 1. As we can see from Fig. 1 resonant amplitudes in ammonia-modified oak are by 4.46 times lower than those in unmodified. For illustrated case, average coefficient of damping in unmodified wood (0.01228) was by 1.5 times higher than of modified oak. For rest of tested specimens coefficients of damping were in turn higher by 1.4 – 1.9 times.

After completion testing with Timber grader MTG, the same specimens were scanned with acoustic KTU stiffness-strength meter. Stiffness-strength meter measures time-of-flight between transmitter and adapter. Afterwards sound velocity and MOE were calculated under simplified Eq. (1). Comparison results are presented in Table 1.



a

b

Fig. 1. Fast Fourier Transform data: a – unmodified oak; b – modified oak

As seen from the Table 1, MOE values obtained using KTU stiffness meter were up to 29 percent different from those measured with Timber Grader MTG. Supposedly end-to-end measuring with MTG gives lengthwise-generalized MOE values while on-plane positioning of KTU stiffness meter reflect localized within 380 mm zone stiffness properties.

Table 1. MOE of unmodified and modified oak wood

Specimen	MOE, MPa (MTG)	MOE, MPa (US)
Unmodified oak wood		
N1	15109	13534
N2	16150	15812
N3	15931	15114
Modified oak wood		
M1	16685	11860
M2	15818	15733
M3	16588	13382

On average for all specimen values obtained with MTG for unmodified wood, differ from those received with US (KTU) by 2 % – 10 %. For ammonia modified wood differences were even larger – 0.5 % – 29 %. Whether wood modification and resulting structural changes influences in measuring principle (e. g. Lamb wave propagation peculiarities) or it is matter of measuring uncertainties it is still not clear. Special experiments are planned to be focused on clearing-up latter questions.

Next series of experiments dealt with size factor effects on measuring results and accuracy. All specimens have been planed on the same edge by 6 mm for width changing. Ultrasound velocities on new surfaces were measured with US (KTU) tester and recalculation of them into dynamic MOE performed. Longitudinal lengthwise specimen scanning on 10 zones (points) allowed to sense local structural variations.

Results of MOE variation lengthwise when changing specimen width are presented in Figs. 2 and 3. For unmodified (Fig. 2) wood specimen width diminishing causes MOE decrease by 4.1 % – 18.6 % (respective ultrasound velocities fall by 3.8 % – 9.7 %). Near-surface structure of modified wood appear to become more homogenous and less related to the width changes and thus overall size factor effects on measurement accuracy.

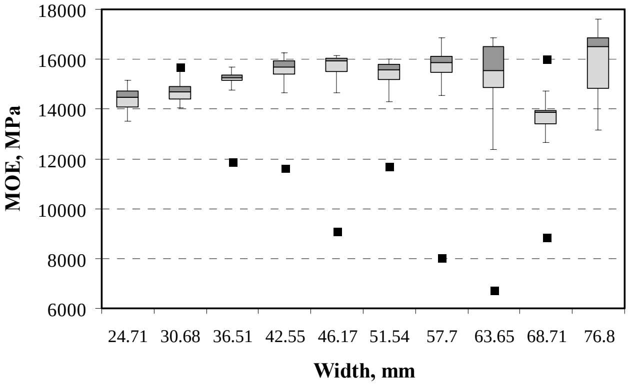


Fig. 2. Box and whiskers plot of MOE variation lengthwise specimen for changing width of unmodified oak

Given example (Fig. 3) indicates that 60 % of MOE values increased from 1 % to 23 %; remaining 40 % of MOE values decreased by 3.4 % – 12%. Still measurements are sensitive to the localization of the ultrasonic tester closer to the specimen ends: MOE values decreases in some cases by 25 % – 35 % when scanning at both ends.

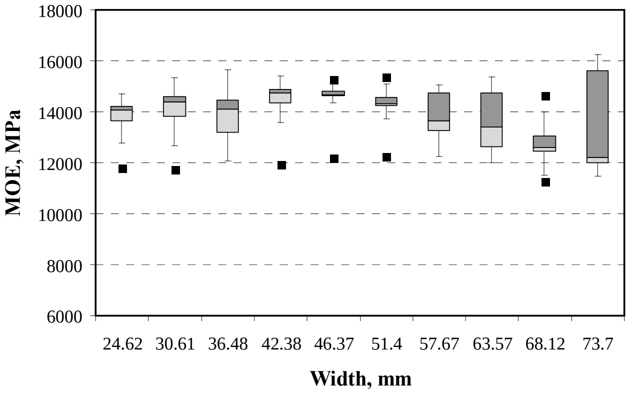


Fig. 3. Box and whiskers plot of MOE variation lengthwise specimen for changing width of modified oak

Similar series of experiments examined dependencies of specimen thickness and lengthwise variation of structure anisotropy on resulting MOE values. Results of MOE variation lengthwise when changing specimen thickness are presented in Figs. 4 and 5.

By nature Lamb wave propagation is not sensitive to the specimen thickness; therefore fluctuation of MOE measures is clearly dependent on tester position (scanning point) and responds the spatial singularities of wood within ultrasound propagation path. For unmodified oak, the decrease of specimen thickness from 24.6 mm to 9.8 mm results in MOE increase by 1.5 % – 25.7 % (Fig. 4); coherent (computational) ultrasound velocity increases by 0.7 % – 13.8 %.

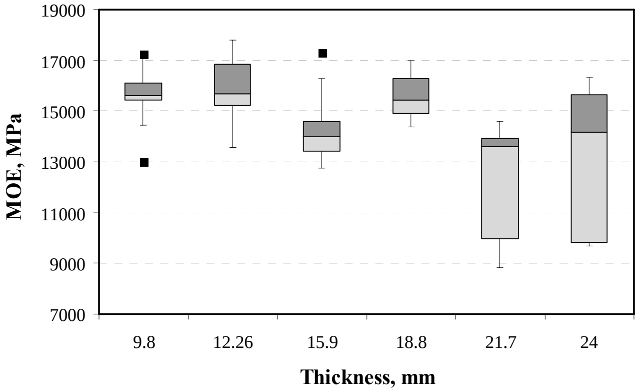


Fig. 4. Box and whiskers plot of MOE variation lengthwise specimen for changing thickness of unmodified oak

Lengthwise MOE variation of modified oak shows larger local anisotropy (Fig. 5). For the same thickness range as above mentioned (unmodified) specimen herein MOE increases by 13.7 % – 44.8 % (ultrasound velocity increases respectively by 3.5 % – 25.7 %). Indirectly those figures indicate that in-homogeneity of tested modified specimen is by 1.74 times higher than that of unmodified.

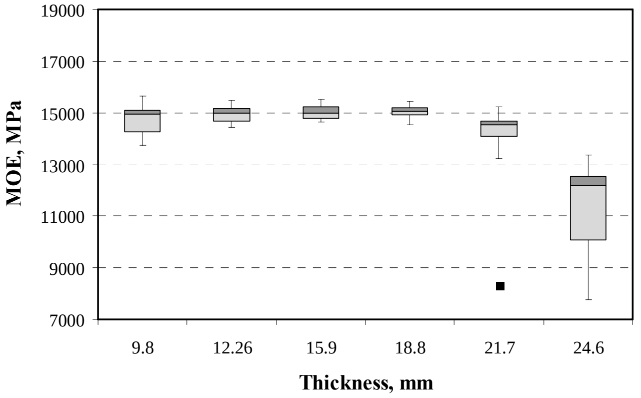


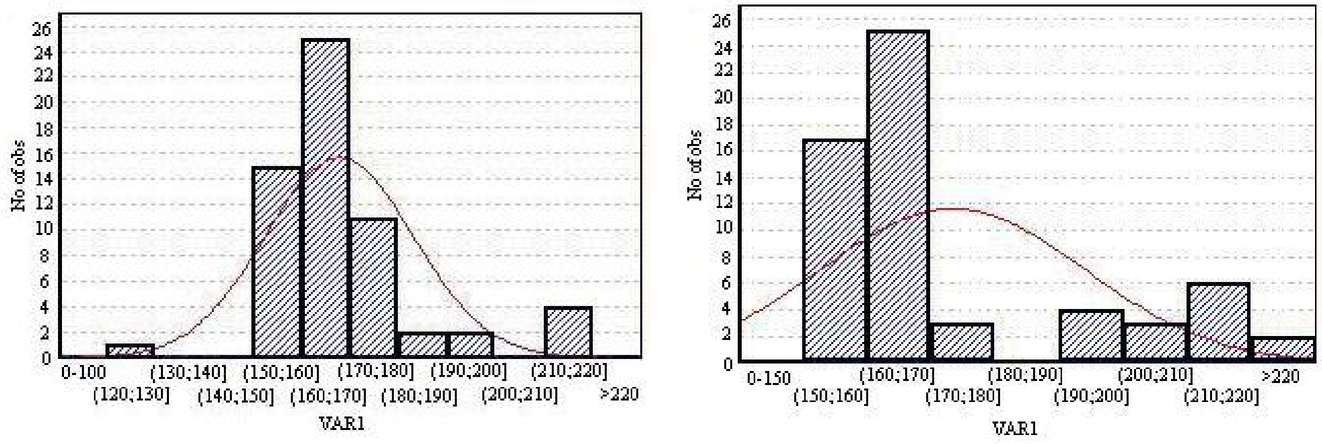
Fig. 5. Box and whiskers plot of MOE variation lengthwise specimen for changing thickness of modified oak

Measurement precision and repeatability for these experiments were very high but changes of measuring coefficients of variation revealed other appearances to be considered. Existence of differences between readings on planed and untouched opposite specimen planes was obtained. Coefficient of variation measuring MOE on planed side S1 is by 27.3 % higher than that on reference side S1 for unmodified wood and by 25.2 % for modified. Coefficients of variation on side S1 remain in the 6.62 % – 11.84% interval. Having in mind extremely low measurement uncertainties of the tester (not exceeding 2 MPa for hardboard [13]), the variability of the results reflects in our opinion actual and apparent internal wood structure changes. Figure 6 presents normal distribution of MOE measurements on planed side S1 for unmodified (Fig. 6, a) and modified (Fig. 6, b) oak wood.

Saltatory character of the graphs reflects zones with local significant in-homogeneities of specimens' internal structure detected by lengthwise Lamb wave scanning. Previous tests on the same specimens with end-to-end MTG tester showed generalized ("averaged") MOE values related to the stiffness of entire timber piece. Evident here is need of complex and simultaneous examination of timber: checking global stiffness and prediction of strength together with lengthwise scanning for detecting local strength-reducing characteristics potentially dangerous to load-bearing capacity.

The same results were obtained when calculating coefficient of variation for MOE changes on planed edge E2. Coefficient of MOE variation when changing width planing edge E2 on that edge was by 64.1 % higher than that on reference edge E1 for unmodified and by 70.9 % for modified oak wood. MOE variation on remainder planes stayed amazingly stable and essentially lower than 3 %. It reflects minor longitudinal structure variety on untouched defect-free surfaces.

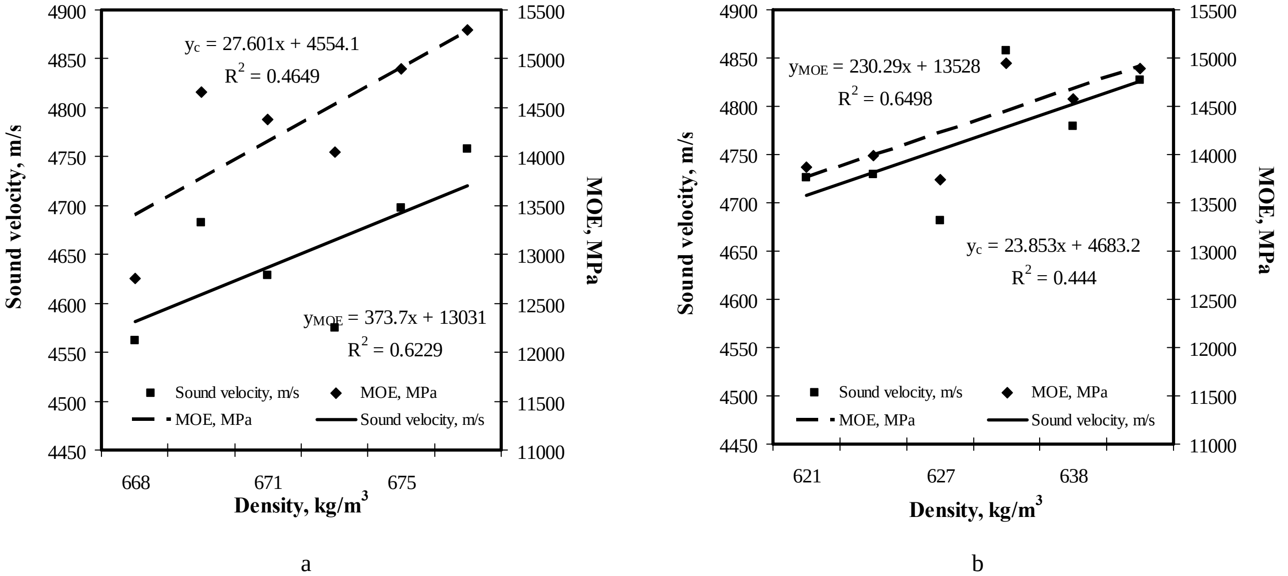
Sequential planing also allowed comparing density changes and respective ultrasound responds for the same specimen. Fig. 7 presents dependences of ultrasound velocity and MOE in wood from minor density changes due to planing for unmodified (Fig. 7, a) and modified wood (Fig. 7, b). Wood density was measured after every planed layer. It was obtained that even little density change influence ultrasound velocity`s and MOE`s values.



a

b

Fig. 6. Normal distribution when changing specimen's thickness (planing on side S1): a – unmodified oak wood (coefficient of variation 9.10 %); b – modified oak wood (coefficient of variation 11.84 %)



a

b

Fig. 7. Ultrasound velocity and MOE dependence on wood density: a – for unmodified wood; b – for modified wood

As we can see from Fig. 7, ultrasound velocity and MOE is directly proportional to the growing density. For unmodified oak wood 1 % growth of wood density increased sound velocity by 3 % (Fig. 7, a) and for modified oak wood 2.7 % growth of wood density increased sound velocity by 2.1 % (Fig. 7, b).

Wood ammonia-treatment influence acoustic and elastic modified wood properties; however, global and local wood anisotropy and un-homogeneity affects testing results too. Experimental validation of vibrant end-to-end tester MTG Timber Grader and ultrasonic on-plane Lamb wave stiffness tester unfolded significant differences of nominal values when testing identical specimen; measuring accuracy and uncertainties also differed. Increased assurance could be achieved when using both testers simultaneously.

CONCLUSIONS

1. Ammonia-modification of oak wood affects and predetermines viscous-elastic properties of oak wood. Resonant amplitudes of ammonia-modified oak decrease by 4.46 times compared with unmodified wood. Coefficient of damping increase by 1.4 – 1.9 times simultaneously.
2. Modulus of elasticity values obtained with vibrant-resonant tester MTG on average differs from those received with ultrasonic KTU tester up to 10 % for unmodified and up to 29 % for ammonia modified wood. Apparently, it relates to the wood plasticization effects alongside with the global and local character of the testers' measurement principles. Recommendable is parallel examination using both methods.
3. Established ultrasound velocity dependency on wood density allows efficient detection of local spatial structural in-homogeneities within timber element.
4. Lamb wave propagation velocity theoretically is not sensitive to specimen thickness; recorded increase of ultrasound velocity in decreasing specimen thickness respond changing anisotropy, early-late wood configuration and hence ultrasonic-detectable stiffness variations.

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